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Beyond the meta-ecosystem? The need for a multi-faceted approach to climate change planning on coastal wetlands: An example from South Uist, Scotland

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ABSTRACT

Exposed, low-lying dune-wetland habitat complexes may have multi-faceted functionality that means they are effectively meta-ecosystems, where inter-acting nearshore, littoral, dune and freshwater components and processes must be considered together, sometimes in conjunction with interactions with contiguous inland habitats. The low-lying dune-machair-marsh-loch (lake) ecosystems of South Uist, Benbecula and North Uist in the Outer Hebrides of Scotland exhibit such functionality, and investigation of a former loch basin at the south end of South Uist has revealed an unexpected level of complexity that also identifies a particularly high exposure to climate change in the coastal hinterland, particularly in terms of water relationships, though the possibility of significant change to the coastal frontage must also be considered in contingency planning. This investigation is described by sector, then drawn together in the context of climate change. It is suggested that the environmental setting of the Uists conforms to the concept of the meta-ecosystem in spatial terms, but with additional legacy and socio-economic components, so that there is effectively a socio-spatio-temporal meta-ecosystem. It is vital that this complexity is understood and accommodated in all flood contingency and adaptation planning, and the paper attempts to assist this by presenting an overview of the functional role and context of water in the coastal lowlands of the Uists.

1. Introduction

It is a truism to assert that an island is an area of land surrounded by water, but in terms of temperate coastal islands such as the Outer Hebrides (Fig. 1), this can mean that they are surrounded laterally by the sea, below by a water table, on the surface in the form of numerous standing waters, and above in the form of precipitation; efficient dispersal of this precipitation is critically important to maintenance of current land management.

The islands of South Uist, Benbecula and North Uist and their satellite islands, collectively known as the Uists, lie off the north-west coast of Scotland (Fig. 1), seemingly exposed to the full fetch of the Atlantic on their western seaboards. Their western coasts consist of an extensive ‘machair’, an extreme form of dune grassland extending up to 2 km inland, defined in terms of its morphology (generally flat and low-lying, mainly below 10 m OD (Ordnance Datum)), high winter water table, sands with a high calcareous, shell-derived component, an oceanic climate characterised by high winds and humidity, and a history of human management (Ritchie, 1979; Angus, 2006). The machair is usually fronted by a higher dune ridge, and in the Uists tends to have a negative gradient with a chain of marshes and lochs (lakes) straddling the machair's inland boundary. The lochs are extremely low-lying, so that they may be brackish where sea water gains access and, in addition to a salinity gradient, may also have a pH gradient. The integrity of the dune ridge is critical to the protection of the inland habitats from marine overtopping or, if breached, marine incursion, and the entire dune-machair-marsh-loch complex or ‘machair system’ is of high natural heritage value (Angus, 1994, 1996).

In a landscape so low-lying and vulnerable to flooding from the sea and from rainfall, it is vital that water relationships are fully understood so that adaptation planning is as well-informed as it can be. Despite a long-standing awareness of the complex inter-relationships of this system and the importance of inland water (Ritchie, 1966, 1979, 2006; Muir et al., 2014), even the most recent strategic planning (Comhairle nan Eilean Siar, 2016) co-ordinated by the Local Authority in partnership with Scottish Water and the Scottish Environment Protection Agency (SEPA), and informed by SEPA's *Flood Risk Management Strategy* (SEPA, 2015), concentrates on civil vulnerability: the aim of the current study is to inform the next phase of strategic planning in respect of the wider function and context of marine and inland flooding in the

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Fig. 1. Situation of South Uist, Outer Hebrides. © Crown copyright and database rights 2018 OS 100017908.

western lowlands of the Uists.

The *Local Flood Risk Management Plan* (Comhairle nan Eilean Siar, 2016) was designed to integrate with other plans and undertakes to consult with the statutory adviser Scottish Natural Heritage (SNH) in respect of actions that might impact the natural heritage, but does not directly address environmental function. SNH does not yet have a detailed local climate change strategy for the Uist coasts and the current work is designed as a contribution to any such strategy that might be developed, as well as to wider flood risk management.

The history of the drainage network is of considerable importance in nature conservation and land use contexts, as it informs the likely behaviour of water – fresh and saline – in respect of climate change. Lochs and saline lagoons, and their associated marshes and swamps, form important components of the designated nature conservation features of the Uists, but the interconnectivity of surface and subsoil water means that aquatic connectivity is of vital importance to all low-lying habitats. Because changing one aspect can have impacts elsewhere, it is vital that this connectivity is well understood in adaptation planning. Each Site of Special Scientific Interest (SSSI) has a list of Operations Requiring Consent (ORCs) but neither the SSSI network nor its associated ORCs are currently equipped to address the challenges posed by the extreme aquatic connectivity evident within the western coastlands of South Uist and Benbecula, or the possible impacts of climate change on this connectivity.

2. Marine processes of coastal significance

Few rocky headlands interrupt the sandy beach that fronts almost all of the west coast of South Uist. The sand, which has a very high proportion of shell fragments, is now largely littoral and terrestrial, having been deposited there by marine and aeolian processes over millennia. The sublittoral is predominantly rocky, and the low gradient that distinguishes the machair terrains is also evident offshore, where the 20 m contour (Chart Datum) lies some 7 km west of Low Water Spring Tide (LWST) (Admiralty Chart 2772). This shallow, rocky platform supports a vast forest of kelp *Laminaria hyperborea*, and the combined rocky seabed and kelp bed lie at a depth that interacts with the wave base, so that despite the vast fetch of the Atlantic waves, they have been deprived of a significant proportion of their energy by the time they crash on the western shores of the Uists (Angus and Rennie, 2014). The growth response of kelp to Relative Sea Level Rise (RSLR) is unknown, but it is possible that in the [usually] clear waters west of the Hebrides, responses would not include upward growth and, even if they did, this might involve additional stipe (stem) flexibility and thus possible reduction of the wave attenuation function. Beach-cast *Laminaria* is used by crofters (agricultural smallholders) to fertilise fodder grain crops on the sandy machair soil of the Uists, where the algae supply not only nutrients but a binding medium, useful when bare sand has been exposed by ploughing in a windy environment; machair crops fertilised with algae appear to have a higher botanical diversity than those fertilised with commercial fertiliser (Angus, 2017a). When left on the shore, beach-cast algae also provide a nutrient-rich rooting medium in sand for strandline plants that can build into foredune, occasionally persisting sufficiently to provide additional protection for the coastal frontage (Angus, 2017a). Breakdown and shedding of kelp also contribute high levels of Particulate Organic Matter (POM) and Dissolved Organic Matter (DOM) to coastal waters, both of which play a vital role in driving inshore marine and littoral ecosystems (Orr, 2013). Beaches with high wrack deposition tend to have a finer grain size and support higher biomass than would be expected in such exposed situations and the ecosystems of kelp beds and sandy beaches of the Uists have been described as “tightly linked” (Orr, 2013). Beach-cast kelp thus not only has a littoral and coastal influence on beach and strandline ecology and sand build-up, but its importation to the machair as fertiliser by crofters transfers marine productivity inland where it then has a positive influence on biodiversity.

3. Water table

The Uist machairs have a high winter water table that is in surplus over extensive areas in winter, while the summer water table is low (Ritchie, 1979). The winter situation involves a series of linear seasonal lochs behind the dune ridge; the lochs have neither inflow nor outflow and are best regarded as surplus water table. These were subject to salinity measurement within four weeks of a major storm in January 2005 that involved extensive marine overtopping, so that even accounting for a dilution of the marine flood water by existing inland surface waters, salinity should have remained high (approaching the 35.00 of sea water), but instead was around 20% of the salinity of sea water. With no surface flushing mechanism available, it was suggested that the lochs had interacted with the subsoil water table, in an attempt to bring the two to equilibrium, i.e. the saline flood had salinized the subsoil water table (Angus and Rennie, 2014). Though this is a superb adaptation for recovery of surface waters following a short-lived storm in which flood waters disperse quickly or a very localised marine flood, such an adaptation becomes a liability if the flood is prolonged, e.g. by blocked drains or a sequence of several storms involving overtopping, and the water table becomes saline over a wide area, perhaps including areas scheduled for cultivation in the following spring. The duration and areal extent of such saline influence on the water table are not known. Beach discharge of fresh water testifies to subsurface seaward flow via groundwater forcing (Ritchie, 1966); such subsurface flow is well-known in dune water tables (Davy et al., 2010) but rate of flow is unknown.

4. Precipitation

Annual precipitation in the Uists is around 1200 mm with the driest months in April to June and the wettest October–January (Table 1). Comparing the two long-term data series, monthly precipitation is increasing in January–April. Local perceptions of increasingly wet soils at the time of ploughing are thus justified. An increase is also evident in August, coinciding with harvest of machair crops. Decreases in May, June and July coincide with the main crop growth, exacerbating any problem of drought at a time of year when water tables are low. The

Table 1
1961–1980 figures from Meteorological Office (1989) and are from Benbecula, 1981–2010 figures for South Uist Range from https://www.metoffice.gov.uk/public/weather/climate/gf4z088dj.

Month	1961–1980	1981–2010
January	129	140.1
February	86	94.9
March	89	104.3
April	62	67.3
May	65	58.3
June	76	61.7
July	83	77.7
August	83	100.5
September	119	105.4
October	139	136.2
November	140	128.9
December	132	118.4
Total	**1203**	**1193.5**

high biodiversity delivered by machair crops is a product of active, skilled crofting (Angus, 2001) and climate trends could discourage cropping in an environment that is already agriculturally marginal.

Kay et al. (2011) suggest that precipitation in NW Scotland could rise as a result of climate change, with scenarios involving increases ranging from 6% to 45% by the 2080s. Any increase in the higher part of this range would pose serious problems for discharge of surplus water to the sea and might also reduce the salinity of saline lagoons, even where increases in fresh water inflow were countered by increasing sea water inflow as a result of RSLR.

5. Loch basins

It has been widely suggested that prior to their drainage the loch networks of Benbecula and South Uist were so extensive they were used as navigable waterways (e.g. Ritchie, 1966; Parker Pearson, 2012). There are four major loch basins in South Uist (Fig. 2). Loch Bi remains extensive and though there is water management, this involved the extension of the loch eastwards by excavation to form a link with the Minch; this connection is valved, as is the sea exchange in the northwest. South of Loch Bi, the Howmore network is more difficult to recreate as a linked system, but the network of drains within the catchment is testimony to major intervention in a formerly more extensive inland water network. The sea enters the estuary of the Howmore River at high tide, so that lochs connected to the estuary are saline lagoons, some of which have onward connections to other lochs. The Olaidh network connects to the Minch via a system of lochs and channels that allows entry of sea water, so that the water body nearest the east coast, Loch Ceann a'Bhaigh, is a saline lagoon (Angus, in press).

There appear to be only two contemporary (or near-contemporary) accounts of the early stages of drainage, both of which refer to a fourth major basin at the south end of South Uist. Walker (visited 1771), reported that "Loch Dalbrog in the South part of the Island, has been lately drained by Mr McDonnel of Boysdale, though immediately adjacent to the Sea, and its Bed 6 feet [ca 2 m] below high Water Mark. This is the first experiment that has been made in the Island, and by draining this Lake, about 2 square Miles [ca 518 ha] have been gained, which is now the richest Land in Wist [Uist]" (Mackay, 1980). The "first experiment" is believed to refer to drainage rather than a canal, as canals that had only a minor impact on loch area had been constructed on the neighbouring Olaidh catchment in the early 1700s (Angus, in press). Anderson (1785) gave a more detailed account of the context for this drainage: the "chain of fresh-water lochs" west of Loch Boisdale, had no connection to the east, and discharged via a single outlet to the west [Roe Glas], that was "frequently choaked [choked] up by the sand". By opening a ditch "of five or six feet deep" (up to 2 m) connecting this chain of lochs to Loch Boisdale, "he [Clanranald's Factor,

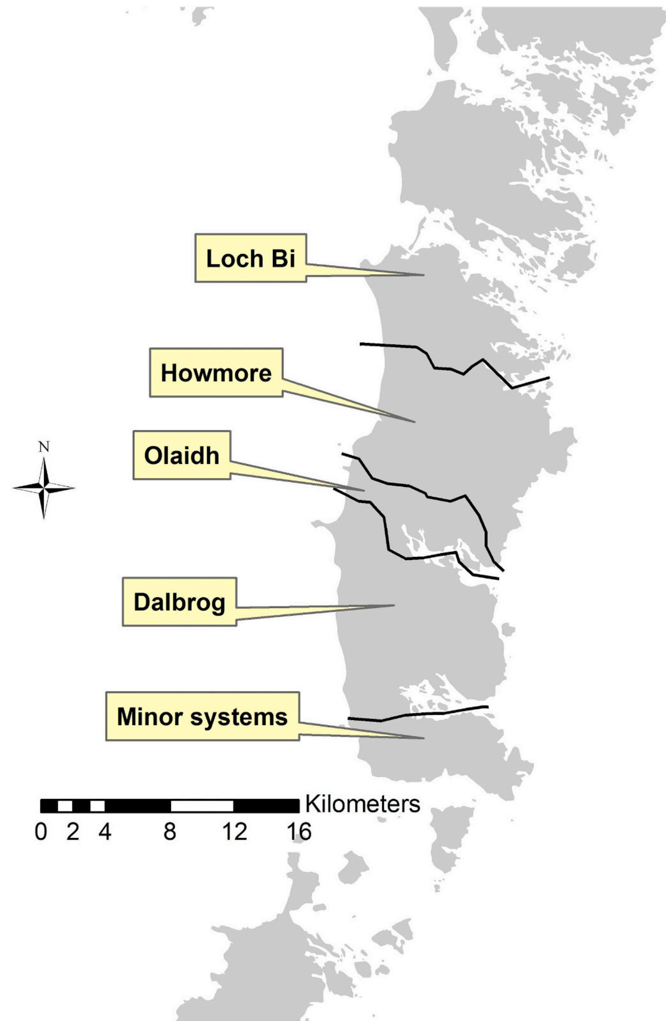

Fig. 2. Boundaries of main drainage basins in South Uist. © Crown copyright and database rights 2018 OS 100017908.

his brother 'Boisdale'] not only lowered the surface of the water in these lochs so much as to gain about nine hundred [Scotch] acres of land, but also established a communication by water, in boats, from the east sea, to almost every single farm on the island". Nine hundred Scotch acres correspond to around 460 hectares, which by the measuring standards of the time is roughly compatible with the 518 ha reckoned by Walker. The emphasis on drainage in these accounts is believed to be retrospective, in that the intention in excavating a channel from Loch Dalbrog to the east coast had been to provide a navigable link, and the drainage was an unintended consequence that proved to be of immense agricultural value, especially towards the end of the 18th century when carts and tracks began to replace boats as a means of transport, making the high water levels required for navigability less important.

Anderson (1785) was clear that there had only been one outlet to the sea for this large loch prior to the construction of the east channel, and that it was frequently blocked. The only feasible location for this outflow is the Roe Glas (Fig. 7). This route was later deliberately blocked, and it is possible that the replacement route to the north (the southern arm of the 'Y' in Fig. 8, was initially constructed as a canal, subsequently becoming a drain, but there is no written record or local tradition of such a canal. Anderson (1785) makes it clear that there were problems with the natural western outlet and that the eastern one was the first such construction; it is unlikely that a constructed canal on the west coast would have gone unremarked after the dates of their accounts, and despite its considerable depth and width, it was almost

certainly built as a drain. The northern arm of the ‘Y’ is known to have been a later construction, believed to have been required by the collapse of culverts in the older, southern section.

If the loch was indeed used for navigation and the carriage of heavy goods, then a link to the east, giving a direct connection to Minch and providing access to and from the clan's lands on the mainland and Inner Hebrides would clearly be useful. Both Anderson (1785) and Walker (Mackay, 1980) credit Clanranald's brother and Factor, Alexander Macdonald of Boisdale, with such work, and their timeline suggests construction around 1740-45. The Clanranald papers, held in the National Archive of Scotland, include a document dated 25 June 1744 from Rory McNeill [of Trumpan] to [?Clanranald]. “Sends 4 jumpers [for blasting] and other implements. At Noontoun [Nunton]” (GD201/4/48), and it is possible that these explosives were used to assist in the excavation of the rocky sections of the channel, so that a date around 1744 can be tentatively assigned to the work.

6. Loch basins reconstructed

At a flood level of more than 3.1 m OD, the Dalbrog loch complex becomes a single unit with outflows on both Atlantic (west) and Minch (east) coasts, so that it is a bifurcated loch (outflows on two coasts), an attribute shared with Loch Bi. Though the eastern outflows of both systems are constructed rather than natural, these are believed to be the only bifurcated lochs in the British Isles, and bifurcation with two-way flows on the coasts provides aquatic connectivity between east and west coasts across two of the four South Uist catchments.

Ritchie (1966) gives 1960s levels for three lochs within the Dalbrog system (Table 2), all of which are very close to levels now revealed by the IFSAR Digital Terrain Model (DTM) (the LiDAR sensor with superior resolution used in the Uists does not give water levels). Loch levels fluctuate and are normally significantly higher in winter, and Loch Dalbrog and its satellite lochs could have been particularly high if the outlet was ‘choaked up’ as reported by Anderson (1785) after heavy rainfall (see Table 3).

It is possible to view Bald's Estate map of 1805 (Fig. 4) as an indicator of progress in the drainage of the Dalbrog basin. This can then be compared with the 1:63 360 Ordnance Survey map of 1947 (Fig. 5), where the loch distribution more closely follows its modern layout, though with an additional water body, Loch A'Ghearraidh Dhuibh, to the west of Loch Dun na Cille, in a location now occupied by the ‘canal’, the main drain at Cille Pheadair, transferring the ambiguity of terminology from Gaelic, where ‘ligeadh’ (various spellings) was used to denote both drains and canals. Wedderspoon (1912) refers to the “old Loch” at Cille Pheadair, describing an area of inland sandflats, and it is clear that the work begun by Boisdale in or around 1744 was a gradual process, with the transformation from Loch Dalbrog to its modern remnants taking over 200 years.

Ritchie (1966) observed a ‘fossil’ bank in many of the lochs of the catchment of the former Loch Dalbrog corresponding to an older water level some ‘3–4 feet’ (c. 1–1.3 m) above current levels (Table 2). The levels of fossil loch banks obtained by Ritchie (1966) were not dated,

Table 2
Surveyed modern loch levels in Dalbrog catchment (from Ritchie, 1966) and IFSAR levels, with possible pre-drainage additional height of 3–4 feet also given by adding a nominal metric equivalent (IFSAR + 1.2 m). Though Ritchie's levels may be in decimal feet, there is very little difference between a tenth of a foot and an inch (twelfth of a foot). All levels refer to Ordnance Datum (OD). The column on the right depicts the levels of the ‘old’ loch shores measured by Ritchie, and gives a ‘standard’ old loch level of 2.4 m OD.

Loch	Ritchie (ft)	Ritchie (m)	IFSAR	IFSAR + 1.2 m
Loch Bhornais	4.4	1.33	1.2	2.4
Loch Hallan	3.0	0.92	1.2	2.4
Loch Aird an Sgairbh	3.5	1.08	1.1	2.3

Table 3
Area of Loch Dalbrog system at the flood levels used in the flood visualisations.

Loch level (m OD)	Area (ha) (GIS analysis of IFSAR DTM)
2.0	460.1
2.4	612.0 (460.1 + 151.9)
2.8	778.8 (612 + 166.8)
3.3	956.7 (778.8 + 177.9)

and may well represent one of the more recent phases in the sequential drainage of the Dalbrog catchment. The IFSAR DTM was ‘flooded’ using ESRI ArcGIS to 2.4 m, believed to correspond to Ritchie's former loch levels, then an additional 0.9 m was added to his measured fossil banks to account for possible older banks and/or periods of very high water levels, thus [tentatively] reconstructing the pre-drainage loch network of South Uist and Benbecula at a surface level of 3.3 m OD.

The level of Mean High Water Spring tide in western South Uist is 2.03 m (Fitton et al., 2017) and data loggers in Loch Bi, a large saline lagoon at the north end of South Uist, reached 2.85 m in the winter of 2015–16 (SNH, unpublished data) despite water regulation, and the extreme level reached by the marine flood of South Uist in the storm of January 2005 was 4.6 m (Angus and Rennie, 2014), so the chosen level of 3.3 m is justified on the assumption that boats were most likely to be used for transport when water levels were particularly high. It should be noted that today there are differences in level between connected lochs, and surface levels of lochs fluctuate in response to precipitation and surface run-off, giving additional justification for the use of indicative water levels in this study. The old records such as the chorography [text] accompanying the Blaeu map (Blaeu, 1654) note the problems caused by fluctuating water levels, and it may be that periods of flooding were used to move goods by boat to places or via routes only accessible at times of peak water levels. These would also have coincided with the maximum water levels in the chain of seasonal lochs behind the dunes, offering the best opportunities to move freight by boats between catchments.

The first published map of the Uists that is more than a very rough sketch is given in the Blaeu atlas of 1654 (Fig. 3), but this is known to be based on unpublished information supplied by Timothy Pont, who is believed to have visited the Uists around 1595 (Parker Pearson, 2012). The two surviving Pont fragments and the Blaeu map show a linked chain of lochs, with several interruptions, from Cille Pheadair to Iochdar (Parker Pearson, 2012). Raven (2012) has provided a concordance for many lochs in the Pont and Blaeu maps using modern names. Stone (1989) has pointed out that the west coast is more detailed on the Pont/Blaeu maps, and that it possible that Pont did not visit the east coast, while Gill Maclean, a historical geographer who lived in Howmore, believed that the detail of Pont's maps showed he had travelled within South Uist by boat (Fleming and Woolf, 1992), an argument endorsed by Parker Pearson (2012). The Pont maps and their Blaeu derivatives are thus of major importance in any attempt to construct a pre-drainage loch network for South Uist, despite their crude outlines, and the chain of interlinked lochs on these early maps is compatible with a reconstructed Loch Dalbrog system, with its northern limit at Loch Toronais (Fig. 7).

The extent of the wider modelled Loch Dalbrog was overlain with national datasets representing archaeological sites (listed monuments, scheduled monuments and CANMORE) and the only such sites within the area occupied by the old loch were duns (forts) and crannogs (artificial islands), both of which would be (crannogs) or could be (duns) associated with lochs rather than dry land. This suggests, though does not prove, that the reconstructed loch beds are likely to be accurate, in that no terrestrial structures have been identified within the area believed to have been covered by the lochs, in an archaeologically rich area extremely well surveyed by archaeologists (Parker Pearson, 2012).

Using the flood model to obtain an outline of the loch, the 1744

Fig. 3. Blaeu (1674) map of southern South Uist based on survey by Timothy Pont (c. 1595). Reproduced with the permission of the National Library of Scotland http://maps.nls.uk/view/00000489.

'canal' distance from its probable eastern margin to Loch nan Ramh via Crois Dughaill is 998 m. The distance from Loch nan Ramh to the main body of Loch Boisdale is 890 m, but some of this channel could be natural. This sea exchange was sluiced at a later date, and is now valved at the Strom Dearg (Fig. 6). Though the valve leaks, saline influence is not believed to penetrate far inland beyond the sluices.

The former loch bed has now become machair habitat and is managed as croft land (tenanted smallholdings with associated land held in common). Part of this drained area, together with remnant lochs, is designated as Special Area of Conservation with a rather larger area designated as Site of Special Scientific Interest and/or Special Protection Area. The maintenance of this land use and its associated nature conservation interest is dependent on continuity of crofting agriculture which in turn depends on the maintenance of the artificial drainage network.

7. Loch basin bathymetry and navigability

Though a LiDAR-derived Digital Terrain Model DTM) (1 m grid size, ± 0.4 m horizontal, ± 0.15 m vertical) exists for the western coastal strip, it does not extend sufficiently far inland to permit a reconstruction of the loch network by 'flooding' the DTM. Accordingly, a coarser DTM derived from IFSAR (5 m grid size, ± 12.5 m horizontal, ± 1 m vertical) was employed that has full Scottish coverage.

In order to measure the area of the loch at a range of flood levels, a polygon Area of Interest (AOI) was created in ArcMap by enclosing the loch as flooded to its maximum level, excluding any water body believed never to have been linked to this water body. The AOI had an area of 1797.2 ha. The areas within each flood range were calculated using Spatial Analyst. Areas of current lochs within the AOI were calculated using the 'inland water' category in Ordnance Survey MasterMap, giving 196 features with a total area of 282 ha. The calculation was re-run using Vector Map District (equivalent to 1:25,000 raster) which yielded 44 features with an area of 283.3 ha. Though it was not possible to eliminate modern drains from these calculations, it is believed that their collective area is small, and that an area of 283 ha is a reasonable compromise between the two analyses. The Loch Dalbrog system had a maximum area (at loch surface 3.3 m OD) of 956.7 ha (Table 3) as opposed to the current loch area of 283 ha, a loss of 673.7 ha.

To obtain a map of former water depth, a maximum flood level of 3.3 m OD was assumed, and using Spatial Analyst within ArcGIS 10.1, the IFSAR DTM value was subtracted from 3.3, and the output was reclassified to give altitude values, resulting in a map of depths at this flood level (Fig. 7). Though depths at lower flood levels can be produced from this dataset, the 3.3 m flood was retained throughout the study.

Attempting to produce a map of water depth is hindered by the lack of information on the depths of current lochs: South Uist was not included in Murray & Pullar's *Bathymetrical survey of the Scottish freshwater lochs* (Murray and Pullar, 1910). Though the existing lochs of western South Uist are known to be shallow, it is reasonable to assume that they represent the deepest parts of the former lochs, given that they are post-drainage relicts. However, modern lochs are represented in the bathymetry model by their surface level (below 3.3 m) as opposed to their depth.

Taking the full extent of Loch Dalbrog and its connected lochs as the loch unit, there are four sections, linked by shallows or by canal. The sections are examined in turn, from south to north, using the bathymetric model (Fig. 7).

The southernmost section of Loch Dalbrog stretches from its southern limit at Baghasdal north to Dalbrog itself (Fig. 7). There is then a stretch of shallower water between An Liana Mhor and the south end of Loch Hallan (Loch Thallan) (Fig. 7), the shallowest part of which is water only with a flood level exceeding 2.8 m OD. This shallow section now has a drain in the western section, but has a distinctly wider profile on the DTMs, giving some support to the possibility of an old navigable link here in the form of a constructed channel or canal.

Once a boat had negotiated these shallows, it would be in the second loch section of Loch Dalbrog corresponding to modern Loch Hallan, where there is a clear, deeper passage north to Aisgernis. There the water would have shallowed slightly, but still allowing navigation to Loch na Liana Moire, where there would have been a water depth of 0.5–1.0 m at a flood level of 3.3 m.

The reconstructed loch map (Fig. 7) shows a clear passage for much of the rest of the route north, then a shallow north for about 400 m before encountering deeper water north of Tobha Aisgernis, in what would have been a southern extension of Loch na Liana Moire. The ridge across the route to modern Loch na Liana Moire is associated with a modern road that crosses the modern drain at NF7335424489.

A large area of shallower water would have been present northwards, west of Frobost, between modern Loch na Liana Moire and Loch Eilean an Staoir (Fig. 7). The Dun in the latter is associated with a submerged harbour (CANMORE) http://canmore.rcahms.gov.uk/en/site/9849/details/south+uist+milton+eilean+an+staoir/.

From Loch Eilean an Staoir there is a clear passage north to Loch

Fig. 4. Detail from Bald (1805) map of South Uist showing southern section of island. Reproduced with the permission of the National Library of Scotland http://maps.nls.uk/counties/rec/657.

Fig. 5. Scanned detail from southern section of Ordnance Survey 1:63360 (one-inch) map of Lochboisdale and Eriskay, Sheet 32, Published 1947, full revision 1928 with later corrections. © Crown copyright and database rights 2018 OS 100017908.

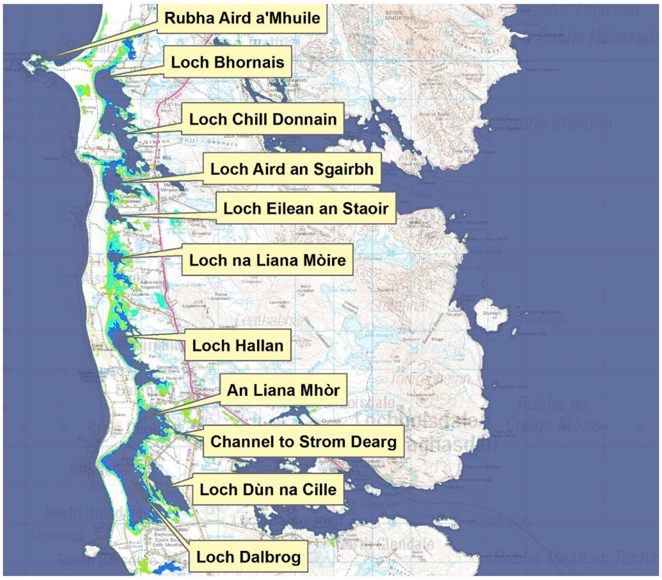

Fig. 6. Flood extent at different flood altitudes, using IFSAR DTM Dark blue = 0–2 m, royal blue = 2–2.4 m, turquoise = 2.4–2.8 m and lime green = 2.8–3.3 m. DTM Data and photography licensed to Scottish Natural Heritage under the PGA, through Next Perspectives. Backdrop © Crown copyright and database rights 2018 OS 100017908. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Chill Donnain (the modern causeway across this loch would have been absent). Though a ridge now separates modern Loch Chill Donnain Uarach (Upper Loch Kildonan) and Loch Bhornais at NF732288, this ridge carries a track, and was constructed in the latter half of the 18th century (Macdonald, 1931) after the lochs had been abandoned for navigation.

Whether these links between the various sections of Loch Dalbrog were natural or constructed is not clear, but the DTM of the link from Loch Bhornais to Loch Toronais gives a very strong impression of canalisation, being significantly wider than the drain that now occupies the western part of the channel. However, the possibility of slumped drain banks cannot be discounted, which would result in a wider depression than the original excavation.

There is thus a case for the existence of a navigable route from Baghasdal (Boisdale) north to Loch Toronais, a distance of 13.2 km, or 40% of the length of South Uist. This extensive system had only one outflow until 1744: the Roe Glas, and when this was choked by sand, the vicinity of the Loch Dalbrog complex would have been extensively flooded due to the shallow gradients.

A salinity measurement taken in Loch Chill Donnain south of the causeway on 8 August 2012 was 2.76, with 0.83 north of the causeway, in Loch Chill Donnain Uarach (S. Angus, unpublished data), confirming that the modern (unvalved) discharge at the Roe Glas allows backflow of sea water up to 1.4 km from the sea that is detectable in both the Cill Donnain lochs. The natural Roe Glas undoubtedly allowed a greater volume of sea water into the system. It is said locally that there is a mooring for boats at the north end of the Dalbrog network, between Loch Bhornais and Loch Toronais, and the Gaelic name for a rock here is translated as 'the rock of the cuddies' ['cuddies' is a vernacular term usually applied to saithe *Pollachius virens*] (Angus Macmillan, Bornish, pers. comm., September 2016), strongly suggesting a marine inflow in the vicinity, probably from the Roe Glas. Wedderspoon (1912) reported a large midden of cockle shells near the Bronze Age settlement at Cladh Hallan, immediately to the west of what is now Loch Hallan (fresh water), towards the south end of the Dalbrog system. Cockles are absent from the exposed western beaches of the Uists and, even allowing for past coastal environments, the nearest cockles would have been at least 5 km away, strongly suggesting that the cockles were obtained from Loch Dalbrog, only a few hundred metres from Cladh Hallan. Sampling of shells from the surface of this midden in June 2016 yielded cockle fragments. The lagoon cockle *Cerastoderma glaucum* is common in Loch Bi in northern South Uist (Angus, 2017b) but the Cladh Hallan fragments were determined as the common cockle *Cerastoderma edule* by Sankurie Pye, Curator of marine invertebrates at the National Museum of Scotland (pers. comm., September 2016). This strongly suggests that

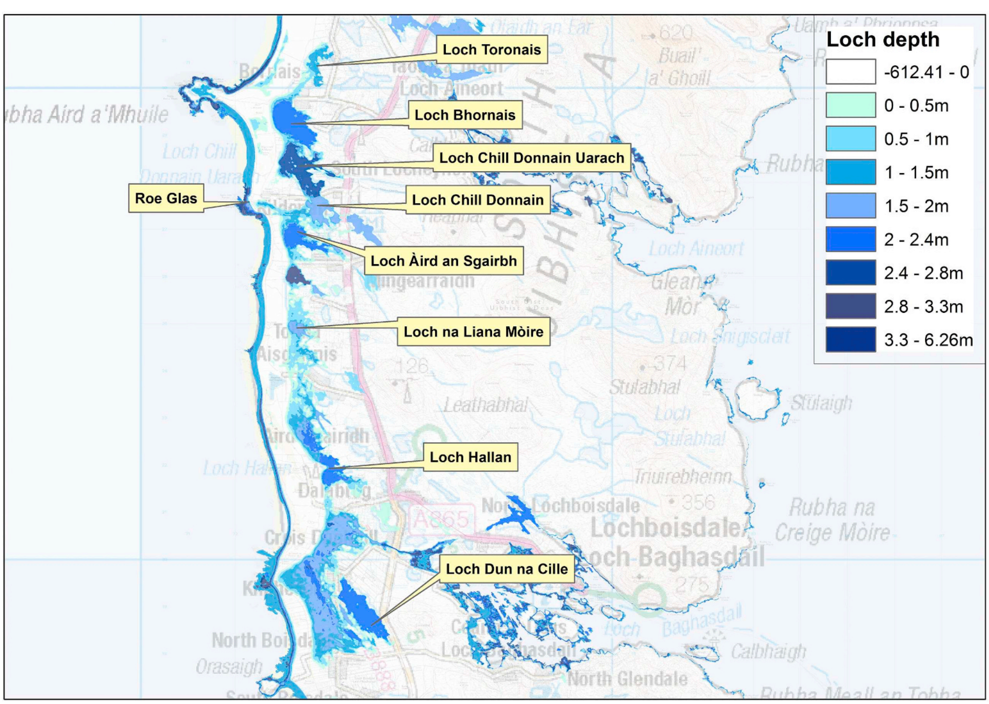

Fig. 7. Modelled bathymetry of Dalbrog loch basin at flood altitude of 3.3 m OD. DTM Data and photography licensed to Scottish Natural Heritage under the PGA, through Next Perspectives. Backdrop © Crown copyright and database rights 2018 OS 100017908.

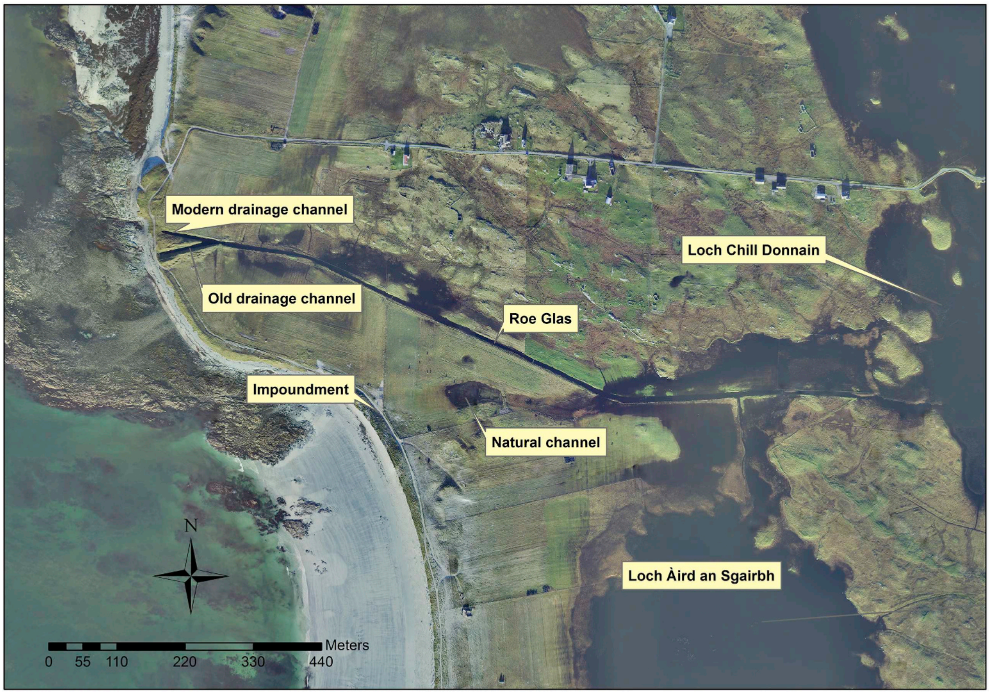

Fig. 8. Roe Glas area showing modern channel and former natural outlet. Aerial image © SNH for Western Isles Data Partnership.

there was a marine link closer to Cladh Hallan than the Roe Glas. The likeliest candidate is via what is now a low, narrow ridge at Cille Pheadair, clearly discernible towards the south in Figs. 6 and 7. Only analysis of diatoms in sediment cores would provide reliable information on past salinity in this area.

As a saline lagoon, the area of 956.7 ha for Loch Dalbrog exceeds the areas of the UK's largest saline lagoons – Loch of Stenness, Orkney (786 ha) and Loch Bi, South Uist (703.5 ha) (Angus, 2017b). With existing saline lagoons at Loch Bi, on the Howmore Estuary, and near the eastern end of the Olaidh catchment, all of them with onward aquatic connectivity, three of the four main catchments of South Uist already have saline intrusion, with a small amount seeping in to the Dalbrog catchment via the two drains. The impact of any increase in loch salinity on the adjacent water table is unknown.

8. Discussion

The construction of the canal from Loch Dalbrog to Loch Boisdale may well have been the most significant anthropogenic environmental impact on the natural environment of the Outer Hebrides since the Neolithic, in that it triggered a widespread drainage programme that utterly transformed the wetlands of the western Uists, with the aim or releasing more land for cultivation. The outcome of the drainage programme was a large area of land and lochs that now lie below the level of MHWS.

With recent observed annual RSLR around 6 mm/yr (Rennie and Hansom, 2011), Angus (2014) has pointed out that Uist drains are reducing in efficiency; not only has the ‘head’ of water between loch surface and low tide surface progressively diminished, but the time available for water discharge from the interior to the sea has correspondingly reduced as the duration of the tidal cycle available for discharge diminishes as RSLR progresses.

There are no sea level rise curves for the Outer Hebrides covering the period 1750–1957, but Orkney occupies a similar position to the Uists in respect of eustatic sea level rise and isostatic recovery, providing a suitable proxy, and Rennie (2006) gives an annual RSLR rate of 0.25 mm/yr for Orkney over the last 2000 years. Uist relative sea level would have risen by 51.75 mm over the 207 year period 1750–1957. The 35 year period between 1957 and 1992 had RSLR rates of 2.2 mm/yr, adding 77 mm, with 6 mm per year thereafter (Rennie and Hansom, 2011), giving a further 150 mm for the period 1992–2017, a total of 278.75 mm (0.279 m) sea level rise since the first drains were emplaced around 1750; assuming that sea level continues to rise at the 1992–2017 rate by 2080 mean sea level will have risen an additional 378 mm, so that sea level will be 656.75 mm higher than it was when the first drains were built. This 0.657 m corresponds to 18.2% of the spring tidal range (Benbecula) of 3.6 m.

RSLR may also have a direct impact on western Uist coastlines beyond any expected from RSLR alone. Chapman (1948) believed that the kelp forest existed down to eight fathoms (14.6 m) but locally extended to 13 fathoms (23.8 m), while in particularly clear waters in the Outer Hebrides it can live as deep as 47 m (Fuller, 1999). The POM debris produced by kelp can be significant, so that kelp might need to grow vertically to obtain sufficient light as RSLR progresses, but it is also possible that waters are relatively clear at times of year that are critical to growth stimulation. The relative importance of seabed and kelp in wave attenuation is poorly understood, but RSLR will certainly raise the wave base progressively above the seabed, so that there is already a higher probability of waves retaining more of their energy on reaching Uist shores. If the possibility of kelp beds not growing upwards to match RSLR is added to this, the probability of more wave energy impacting on the Uist coast becomes significantly higher; even if the fronds do grow upwards, the increased length of the stipe (stalk) is likely to affect interaction with wave energy. Though Lowe et al. (2009) found no evidence of any increase in storm surge frequency or magnitude in recent decades, Castelle et al. (2018) reported increases in winter mean wave height. However, even storms of existing frequency and severity may result in greater coastal impact from RSLR because of reducing wave energy attenuation.

The Storas Uibhist report on drainage (2006) splits the Dalbrog catchment as employed here in two, with a ridge of 3.1 m (as revealed by LiDAR) forming the north-south partition located between Loch Hallan and Loch Eilean an Staoir at Frobost, though they concede that the boundary between the two is “indistinct”. Their ‘Roe’ (north) and ‘Strom’ (south) catchments have areas of 15.8 km^2 and 33.9 km^2 respectively. They would join at flood levels exceeding 3.1 m OD forming

a single ‘Dalbrog’ catchment with an area of 49.7 km^2, applied here on the grounds of the indistinct boundary, the possibility of wind-assisted flow, and on their common history as part of a single loch basin, still linked by subsurface and even surface connections when floods reach problem levels. Land is so level generally in this area that any links will be fully exploited by raised water levels, and the two will flood as a single basin once the level of the flood exceeds the altitude of the Frobost ridge.

This is critically important in adaptation planning, especially in a worst-case scenario involving multiple high-rainfall storms. The situation envisaged here is analogous to that experienced in SW England in the winter of 2013–14, when successive depressions caused severe storm damage and flooding (Thorne, 2014). North Atlantic depressions frequently track further north than this, intercepting Europe in the general region of NW Scotland (Lozano et al., 2004). Such a succession of depressions in the latter half of winter would impact an already saturated landscape. Heavy precipitation exceeding 25 mm in 24 h is by no means infrequent in NW Scotland. On a catchment of 49.7 km^2, this precipitation corresponds to 1242.5 million litres, or 273.3 million gallons. Though the subsurface water table can be regarded as ‘full’ in such circumstances, there is subsurface seaward flow via the sand aquifer, with significant (but unknown) quantities of water discharging in the upper beach (Ritchie, 1966); over a distance of 13.2 km (the sea frontage of the Loch Dalbrog aquifer) this discharge could be substantial, and is likely to be much more significant than any impact of winter evapo-transpiration. Nevertheless, it is likely that a high percentage of the 1242.5 million litres would have to discharge via two outlets: the Roe Glas and the Strom Dearg. Assuming total water surplus (probably never achieved in reality), each 1 mm of rain will contribute 49.7 million litres of water to the Loch Dalbrog catchment which could discharge only via the Strom Dearg or Roe Glas or slowly to the beach by percolation through the dune ridge. The discharge capacities of the Strom Dearg and Roe Glas drains are unknown.

The ability of both drains and of the beach end of the aquifer to discharge are steadily reducing, because sea level is rising. Though the figures given for RSLR refer to mean sea level, levels of low tides are part of this increase. Since 1750 (the date of the commencement of drainage, not the dates of construction of the current facilities) mean sea level has risen by around 0.279 m, which is about 7.75% of a tidal range of 3.6 m. This has additional significance in that this loss has been from the most efficient part of the tidal range in terms of water discharge from the land to the sea, because the greatest difference in water levels between the inland lochs and the sea are when the tide is at its lowest. The discharge will now also be on a higher part of the tidal curve, meaning that there will be less time available to discharge water during any low tide. More seriously, both aspects (level of discharge and time available to discharge) can be dramatically affected by low barometric pressure (i.e. a depression), where each Hectopascal (1 hPa = 1 millibar) below standard atmospheric pressure raises sea level by 1 cm. Atmospheric pressure of (say) 980 hPa would raise sea level by a further 33.5 cm at low tide. The low pressure of the January 2005 storm was 944 hPa, which alone raised sea level by 69 cm, and the Scottish record is considerably lower, at 925.5 hPa. There is thus the potential for a progressively attenuating ability to discharge being significantly impeded at the very time it is most needed – during a low depression with heavy rain: the higher the precipitation and the lower the barometric pressure, the greater the danger of flooding.

The water table is in surplus in the Uists for much of the winter, i.e. the ground is saturated. In a winter scenario involving heavy precipitation, most of the day's rainfall would be retained on the surface of the land, and would flood the drains. Once the drain margins had been reached, the drains would overflow and water would follow the gentle gradients, tending to accumulate where the land is lowest, almost certainly in the beds of the last lochs to be drained, i.e. the former lochs shown on the 1:63,360 Ordnance Survey maps (Fig. 5). Then, if similar rainfall occurred the next day, and the next, a serious inland fresh water flood would be experienced. As seen in January 2005, severe storms can involve marine overtopping of the dune ridge, and this sea water could add to the flood, to be diluted by wind-driven turbulence, converting the fresh water flood to a more saline one. It is known that surface water interacts with the subsurface water table in the machair soils of the Uists (Angus and Rennie, 2014) and there could thus be widespread saline contamination of soils. There are two reasons why this did not happen in 2005: the storm was a dry storm, and the drains coped – except where they were blocked by debris; also, mid-January flood timing allows for several months of rainfall to flush the salt out of the soil prior to the main onset of plant growth. In a storm situation involving widespread fresh-water flooding and marine overtopping, the severity of the impact would depend on the gross amount of water, its salinity, its duration, and the effectiveness of subsequent precipitation-driven leaching of the salt from the soil prior to vegetation growth in spring.

This worst-case scenario now has widespread flooding of the Dalbrog basin, with water accumulating in the beds of the last lochs to be drained, which are just below 1.0 m OD as measured from a LiDAR DTM. The head of water means that even with the low gradients of the area, drain water would be flowing at high speed towards the discharges, possibly at rates rarely experienced since the last lochs were converted to agricultural land. With vegetation at its winter minimum, drain banks would be more prone to erosion from this rapid flow. This would have been known during the period of loch drainage, and this is possibly why some sections of the South Uist main drain or ‘canal’ were stone-lined; with no stones occurring naturally on the machair, strong justification would have been required for such construction. Recent drain clearance has mostly involved machinery, which often removes the stone banks with the accumulated silt and vegetation, so that this former protection is often now missing. Though there is a problem in respect of the erosion itself, its main consequence will be what happens to the erosion product downstream when the incoming tide halts the seaward flow of inland water: the debris, sand and mud will drop to the bottom, and sediment build-up at the discharges could block them completely.

Water discharge is at its most efficient into air, because there is very little resistance, but once the tide has reached the level of the discharge, the drain discharge will decrease, drawing to a halt as the discharge and marine water pressures equalise. Around this stage, any valves will close under their own weight, and where valves are absent or where the valve leaks, the flow will start to reverse as the tide continues to rise.

Ultimately the combination of extreme weather and sea level rise might make passive drainage periodically unworkable, with reduced differences in inland and sea water levels and more limited discharge periods, so that active drainage (pumping) might have to be considered, at least as a contingency. It has been suggested by a local engineer (Mairi Mackenzie, pers. comm., September 2016) that new drains could be added higher in the tidal profile, prolonging discharge times during floods.

RSLR is likely to result in increased saline input to saline lagoons and fresh waters, with any prolonged raised salinity flooding likely to result in salinisation of the water table. The four main loch basins may or may not be linked at water table level: the possibility of former canals linking these exists, despite the absence of any signs of them today: they might well have utilised the chain of seasonal lochs just inland of the active dune ridge, with all traces other than a preserved water table link concealed by subsequent sediment dynamism.

Increased precipitation might have impacts beyond flooding, with the impacts of the flooding itself exacerbated by the removal of old water management infrastructure, none of which is protected by any legislation or even non-statutory listing. Additionally, water entering the machair from the eastern moors might have a pH as low as 4.5, in contrast to water leaving the machair which has a pH of up to 8.1 (Ritchie, 1974). Alterations to the magnitude or direction of the flow of inland water might affect the pH of lochs, in turn affecting their

nutrient status and biota (possibly including commercially important fish populations) while increased levels and flow of fresh water might result in a seasonally variable dynamic tension with saline inflow from rising sea levels, with unknown ecological consequences. Any disincentive for machair cultivation in the form of adverse seasonal changes in precipitation and/or saline infiltration of the croft water table would result in a reduction in machair biodiversity as well as having an adverse impact socio-economically. This reduction in biodiversity would extend beyond the machair fodder crop if the associated store cattle were also abandoned.

Further research on past loch distribution and salinity will inform future strategic flood planning, as will more detailed DTMs and improved understanding of modern aquifer function. Ideally such plans should accommodate an understanding of the extreme habitat connectivity in the Uists: there is continuity of ecological processes from 7 km west of the islands through the littoral, strandline, dune, machair, marshes, lochs and onwards to the east coast via the bifurcated lochs, so that the environment conforms to the concept of a 'meta-ecosystem' as defined by Loreau et al. (2003): "a set of ecosystems connected by spatial flows of energy, materials and organisms across ecosystem boundaries". Arguably the Uists go beyond this in that human intervention is a critical component of environmental function, and as well as the spatial aspect there is a temporal element where past water management has considerable implications for adaptation to climate change, so that understanding of the meta-ecosystem must embrace past and present as well as future management.

This study is designed to inform adaptation rather than attempt to direct it. Adaptation is often regarded as a mechanism designed to protect human rather than environmental assets (Cooper and Pile, 2014) but in the multi-faceted, closely interlinked Uists the distinction may be artificial. The assets are socio-economic, but the social and economic backgrounds are based on cultural aspects such as land use and even language (Gaelic) that in turn are dependent to varying extents on the functionality of the environment. The challenge will be to protect and conserve the entire spectrum of assets on which this interlinked system depends. With such extreme interlinkage and interdependency, the dangers of 'maladaptation' (Brown et al., 2017) are all too real, making the understanding of the complete range of environmental functions essential to the adaptation process. Such understanding may well be the keystone upon which the future of the Uists depends. In such circumstances, misplaced perceptions can detract from the effectiveness of responses. Mobility of the dune ridge may be perceived as 'erosion' and resisted, as identified by Cooper and Pile (2014) but the need for this dune ridge to remain mobile may be a key factor in the maintenance of the wider coastal ecosystem and of the land uses that depend on it. There should also be an understanding that any threat to the integrity of this ridge might come from the land rather than the sea, with an extreme inland flood breaching the ridge from the east, possibly forming a tidal connection between the sea and the extensive inland areas that lie below the altitude of MHWS.

9. Conclusion

Water, in terms of its extent, energy, sediment load, level, and chemistry, is the unifying factor in this meta-ecosystem, with a continuous interaction of associated processes from the outer edge of the kelp beds through the littoral and from there via the lochs and water table as far as the east coast of the islands. The connectivity is extensive, extreme and complex, but planning for future climate change in these vulnerable islands depends on an improved understanding of all the processes involved. It is not just habitats and species that are at risk of fundamental change – so is the way of life of the people who have always been part of this connectivity. Contingency planning for climate change in the Uists must incorporate an understanding of the complete picture of all the processes involved, which includes an appreciation of past environments: to understand where the Uists may be going it is necessary to understand where they have been. Only by appreciating the full range of environmental processes and their onward influences can effective adaptation be achieved. The extreme linkage makes 'maladapation' particularly problematic, in that delivering a 'wrong' solution to a problem in one part of the system can have negative onward consequences. Less obviously, and perhaps more seriously, delivering the 'right' solution for the problems of one facet of the system could be very wrong for other parts of the system. In such a complex situation, knowledge and understanding are of critical importance.

Declaration of interest

None.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.ocecoaman.2018.08.013.

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